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Electrical Impedance Tomography at the A-014 Outfall for Detection of DNAPL

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by

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Introduction

Some laboratory studies (e.g., Olheoft, unpublished report 2001) have shown that the low frequency electrical properties of some soil minerals contaminated by dense non-aqueous phase liquid (DNAPL) may be sufficiently unique to make it possible to use electrical impedance tomography (EIT) to differentiate normal electrical heterogeneities of the subsurface from DNAPL contamination.

The goal of this work is to determine if electrical impedance measurements of the soil and groundwater at a contaminated site can be used to detect the presence and map the distribution of DNAPL. The strategy for achieving this goal is to predict the presence and location of DNAPL from an appropriately processed data set taken at the A-014 outfall site at Savannah River Site, which is suspected of near-surface contamination, and then to compare those predictions with results of sample analysis from the same region. Complete agreement between the predictions and the sampling data will be strong (but not conclusive) evidence that DNAPL contamination alters the subsurface materials in a way that can be detected and mapped using low frequency electrical methods. A total lack of agreement will be interpreted to mean that electrical methods cannot at this time be used to locate contamination. The results will be used to make funding decisions about continuing development of EIT for DNAPL detection.

The laboratory data suggest that three properties of contaminated soil electrical impedance may be useful:

1- Non linear properties of some clays when coated with DNAPL -- Hilbert distortion and harmonics distortion. While these two nonlinear effects can, in principle, be measured *in situ* no one to date has an inversion scheme for imaging them—so it is not possible to actually infer the spatial distribution of contaminant distributions using these properties. Another problem is that these non-linearities are difficult to measure *in situ*, especially since most electrodes used for field surveys produce by themselves a nonlinear response because of the electrical double layer formed at their surface. This response will act to mask the nonlinear response of the soil. In addition, to the best of our knowledge, only Gary Olhoeft has the measurement system needed for the quantification of these distortions. As a result, it is our opinion that these non-linearities will probably be difficult to use.

2- Unique spectral impedance associated with some contaminated clays . Such a spectral response must occur between about 0.01 and 100 Hz to be really useful for the EIT approach. At lower frequencies, data acquisition times required to gather enough data for inversions become very long (one to a few days). These times are not completely unmanageable but are difficult to use in the current research phase where typical experimental conditions require many field data sets. At higher frequencies the field instrumentation and data inversion becomes much more complex and expensive because inductive reactance must be calculated. Fortunately, Olhoeft's lab results indicate that at least some relaxation mechanisms have time constants to produce features in the desired frequency range (see Figure 1). These spectral features are not uniquely produced by contamination. They might also result from unusual (and probably rare) pore size distributions. However, it is our opinion that mapping spectral impedance differences such as this is one of the most promising diagnostic approaches for mapping contaminated soils using EIT. These spectral impedance differences can be measured and imaged using the EIT instrumentation and inversion codes we have available.

3- In addition, we believe that other unusual values in electrical properties or just the spatial distribution of properties might be useful in delineating contamination. Specifically, we have noticed that known contaminated areas can be unusually conductive and/or reactive. Even the laboratory results shown in Figure lab attest to a larger than normal negative phase. We have observed, during some previous (unpublished) work, a large negative phase associated with a diesel fuel spill beneath a large storage tank. A large negative phase as a diagnostic is rather nonspecific to contamination—for example natural ores are conductive and reactive. However, we believe this diagnostic, taken in the geologic context, can be useful.

In this report we will use property 2 above, along with less specific but relevant property 3, to infer the absence or presence of contaminated soil at the A-014 outfall. We will show that the initial evidence (property 3) of a contaminated region was an uncommonly large negative phase anomaly (up to about –350 m rad) reconstructed from a surface survey. We also noticed that this anomaly was located near the outfall, only a few meters below the surface and that no such phases were seen in regions away from the outfall (clean soil?). Then (using property 2 above) we examined the spectral nature of the impedance (magnitude and phase) for this image plane and found that only this already suspect region shows the impedance spectrum between 0.125 and 8.0 Hz that is similar to a laboratory measured spectrum for soil contaminated with PCE.

Experimental Design

We did not request installation of vertical electrode arrays at the site. That decision was made because we felt that project the goals just stated could be accomplished without the expense of drilling. Surface arrays provide limited depth coverage but shallow contamination was evident from the strong odor of PCE noticed during recent shallow excavation of the outfall. In addition, our desire to compare outfall data with clean soil data, was easier and cheaper to satisfy using the long surface arrays that we will describe later.

At the A-014 outfall site we acquired data from 2 surface surveys and 2 cross borehole surveys. These surveys amounted to well over 24,000 individual measurements, of complex resistance (impedance). Figure 2 shows the layout of the surface arrays relative to the borehole array locations used by MIT and Blackhawk. The strategy was to arrange the survey so that both surface image planes contained a region of potentially contaminated soil (southern end, near the outfall) as well as a region of hopefully uncontaminated soil (to the north, away from the outfall). As we mentioned before this ability to compare data from potentially clean and contaminated soil was one of our goals.

Figure 3 and 4 are photos of the site with the approximate location of our two surface survey lines where they cross the outfall. The northern ends of both survey lines are to the left of the field of view.

The railroad track to the west of the outfall (see figure 2) represents a large mass of IP producing metal. However, we believe that it cannot produce a significant influence on the data. Not only is it several dipole lengths from the west survey line, it is electrically isolated from the system by the high resistivity of dry crushed rock in the rail bed.

The lowest frequency we examined (1/8 Hz) was set by practical limitations on available field time. The highest frequency (64 Hz) was set by a need to minimize inductive coupling effects from the data. Even then there are signs of cable coupling at frequencies above 8 Hz. Regrettably, this spectral range is much narrower than that which is available for the laboratory data.

All data in the surface surveys were collected using a dipole-dipole, skip 2 measurement schedule which included all of the reciprocals. The west survey line was aligned with the MES 16 and MES 17 boreholes so that the surface reconstructions could be compared with the cross borehole images. Likewise the east survey was aligned with MES 15 and MES 18. All surface electrodes were porous pot copper-copper sulfate electrodes placed on a one meter spacing as shown in the figure.

Some cross borehole data were acquired for the two planes MES 16-17 and MES 15-18. Because every other electrode in these borehole arrays is a silver-silver chloride electrode and Dale asked that I not use them as current sources, it was not possible to get a full set of reciprocal data for these cross hole planes. For this reason we used a dipole-dipole skip two schedule, supplemented by a cross hole horizontal dipole schedule, modified to remove any use of the non-polarizing electrodes as current sources.

Results

Figure 5 shows the reconstruction for magnitude and phase data from the LLNL east surface array. Figure 6 is the reconstruction for the west array. The surface topography shown around the outfall at the south end of the arrays is included in the forward model. This helps to insure the accuracy of the reconstruction, especially reducing the possibility of spurious anomalies near the surface. Reciprocity of more than 70% of the impedance magnitude measurements were better than 1.0% and algorithm convergence was normal with a normalized squared error of 135/347 (260/318 for the west results). All taken together, these statistics imply that the reconstructions are free of the common problems that might cast doubt on their veracity. Only values to about 6 m depth are plotted because values below this are poorly constrained by the surface data.

Also included on both figures are detailed frequency analysis of selected pixels in each phase image. Between 0.125 and 8 Hz the value in radians of each pixel is plotted to allow comparison with laboratory data in Figure 1. Some of the spectral plots for the magnitude are also shown in the figures.

We also measured the nonlinear effects in our data by taking the reciprocal of each measurement. A comparison of these reciprocal pairs is a measure of non-linearity in the data. Figure 7 documents the reciprocity of the impedance for the 0.5 Hz data from the west surface survey. The impedance magnitude, or resistance, 74% of the data are reciprocal to better than 1% but only 28% of the phases are reciprocal to 1 m rad. These values of 1% and 1 m rad are somewhat arbitrary but do represent typical values that we have used in the past to define standards for data quality. Our experience is that at sites where no contamination is expected, the data are typically not this reciprocal—that is, at most sites less than 74% of the magnitudes are reciprocal to better than 1%.

This data supports the conclusion that if Hilbert distortion or harmonic distortion due to contamination are producing nonlinear data then the effect is small and therefore difficult to use as a diagnostic for contamination. Nevertheless, we will return to this conclusion later to discuss the possibility that even the relatively small reciprocal differences that we measure could be evidence of a non-linearity and therefore evidence for soil contamination.

We will not discuss our reconstructions from the cross borehole data for two reasons. First, half of the electrodes were of the non-polarizing type and were not used as current sources. As a result, very little reciprocal data were available and this made it difficult to obtain convergence in the reconstructions. Second, and more importantly, we used these electrodes because of the courtesy of Dale Morgan who paid for their installation from his project funds. We defer to Dale to present results from those arrays.

Conclusions and Discussion

We believe that currently the most usable field diagnostics for the presence of DNAPL are (1) larger than normal values of phase and (2) the peculiar low frequency phase spectra shown in Figure 1. Both of these properties are clearly shown in the laboratory data of Figure 1. Both of these characteristics should be detectable in field data and so we will use them as diagnostics to examine our results summarized in Figure 5 and 6.

First, we begin with results from the east survey line. We note that the two largest magnitude phase anomalies in Figure 5 must be disregarded because we know that they are most likely caused by measurement or analysis errors. The anomaly in the lower left corner and the one along the lower right edge, both of which are below 5 meters in depth, are poorly constrained by the surface data. The anomaly along the lower right edge may be due to cable coupling (measurement cables were longest for the electrodes on this end of the survey) although we have no direct evidence for that conclusion. At any rate, we have limited our analysis to frequencies of 8 Hz and below because the 32 and 64 Hz data show signs of coupling.

The remaining features in Figure 5 shows a few phase anomalies, all of which are less than 40 m radians and these phase magnitudes are not uncommon for normal, uncontaminated soil types. In addition, these anomalies do not show any spectral features like the contaminated phase spectra shown in Figure 1. Also the potentially contaminated soil (at the south under the outfall) appears similar to the likely uncontaminated soil to the north. Reconstruction of the magnitude (resisitvity) looks normal and adds little to the interpretation. We conclude, therefore, that this survey does not show evidence of contamination within the first 5 meters depth.

Next we examine the results from the west survey line. Here, the reconstruction is for the most part, very much different. Most obvious is the strong contrast features in both phase and magnitude. [note that the color scales are the same for the figures of both survey lines] As in the previous phase reconstruction this one also has evidence for high phase anomalies at the lower left corner and along the bottom right edge. We ignore them for the same reason as before. That leaves three main features in the phase reconstruction centered below electrodes 8, 19 and 25. The feature furthest north, below electrode 25, is only 70 m radian at 8 Hz and the spectrum shows no characteristics of the contaminated lab spectra in Figure 1. We conclude that this is likely a normal response of silty or clayey soil.

The feature below electrode 19 is stronger—about 100 m radian at 8 Hz—and there is slight evidence of a phase peak near 2 Hz. Notice also that the pixel at the edge of this feature shows a small dip at 4 Hz. Taken all together these data suggest phase response like a contaminated soil (Figure 1) but the evidence is weak.

The feature below electrode 8 is very strong with phase angles up to –400 m radian. This is an IP response typical of highly mineralized ores like iron sulfide but the geologic environment makes this very unlikely. We have plotted the spectra of this anomaly at three different pixels and each shows a characteristic phase minimum and maximum near 1Hz. The impedance magnitude (resistivity) reconstructed in the lower panel of the figure shows a more resistive soil associated with the phase anomaly and this also is consistent with the contaminated sample data in Figure 1. The phase spectra and magnitude, together suggest the soil in this region is responding electrically like the DNAPL contaminated, laboratory soil sample. The north end of the images (most likely clean soil) do not show these features.

Because these reconstructions are from surface data only the spatial resolution of these images is not sufficient to inform us about the fine distribution of what is causing this anomaly. We cannot say, for example, if the structure is from closely spaced silt or clay bedding. This type of resolution, as well as information on deeper soils, might be available from cross borehole data.

If this anomaly is a result of DNAPL contamination then it may be possible to identify nonlinear effects such as Hilbert or harmonic distortion that this region might produce as reported from previous laboratory studies. To examine this possibility we return to the field data and compare the reciprocity (a measure of non-linearity) from data taken at the north and south ends of the west survey line. The proposed contamination lies only beneath the south end of the line. Measurements taken only over this end of the line should produce larger reciprocal differences than those taken over the other end of the line. Figure 8 shows us that the data from each end of that survey line have similar distributions of reciprocity; if significant non-linear effects were caused by the possibly contaminated soil near the south end, Figure 8 would have shown larger reciprocal differences for the south data. We conclude that if there is a contamination beneath the outfall it does not generate readily observable non-linearity in the data. If the nonlinear component is this small, then of course, it will be difficult to use to identify contamination. Therefore, our analysis suggests that possible non-linear effects associated with contamination appear to be small and similar to non-linearity observed in clean soil.

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Figures

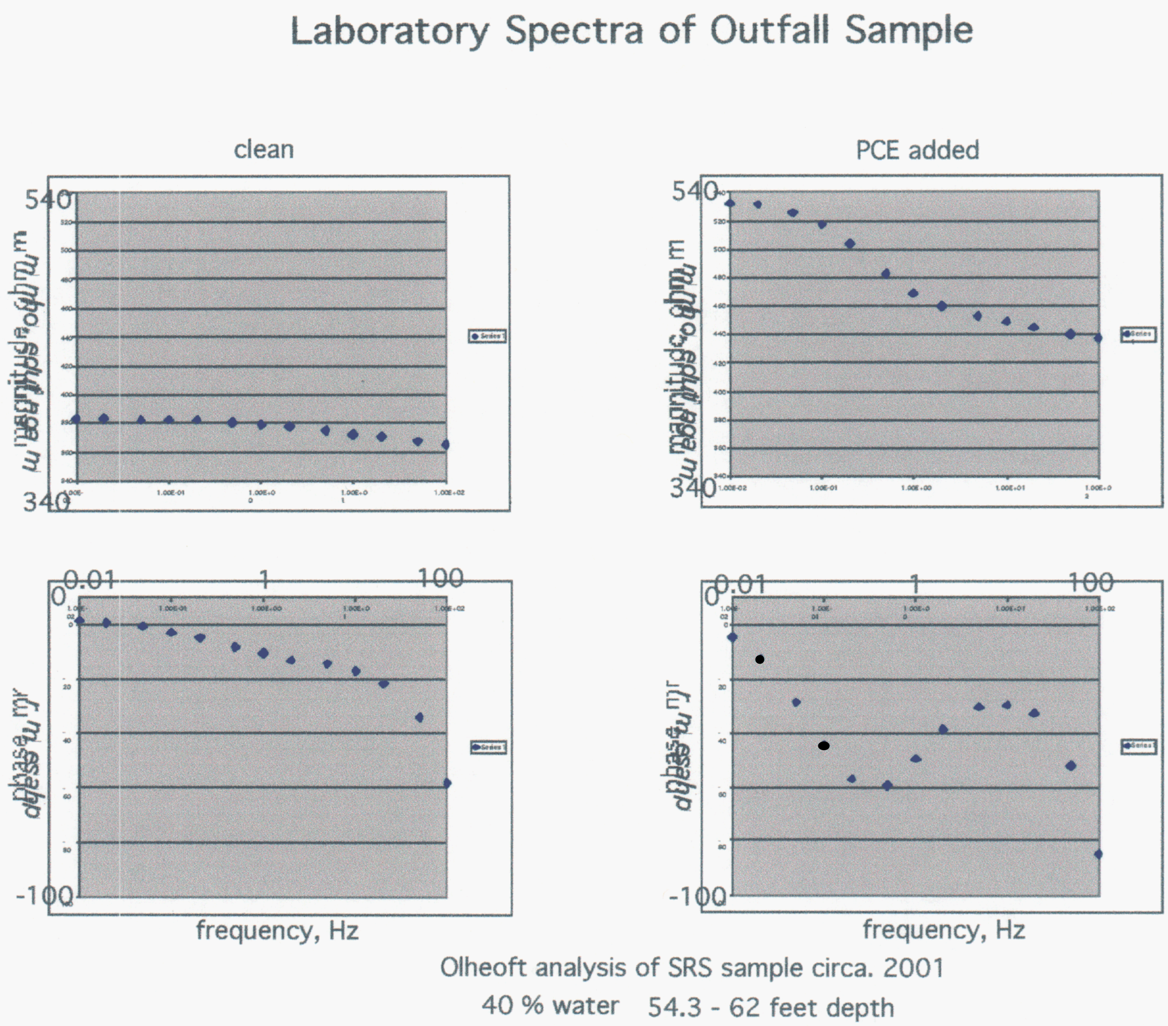
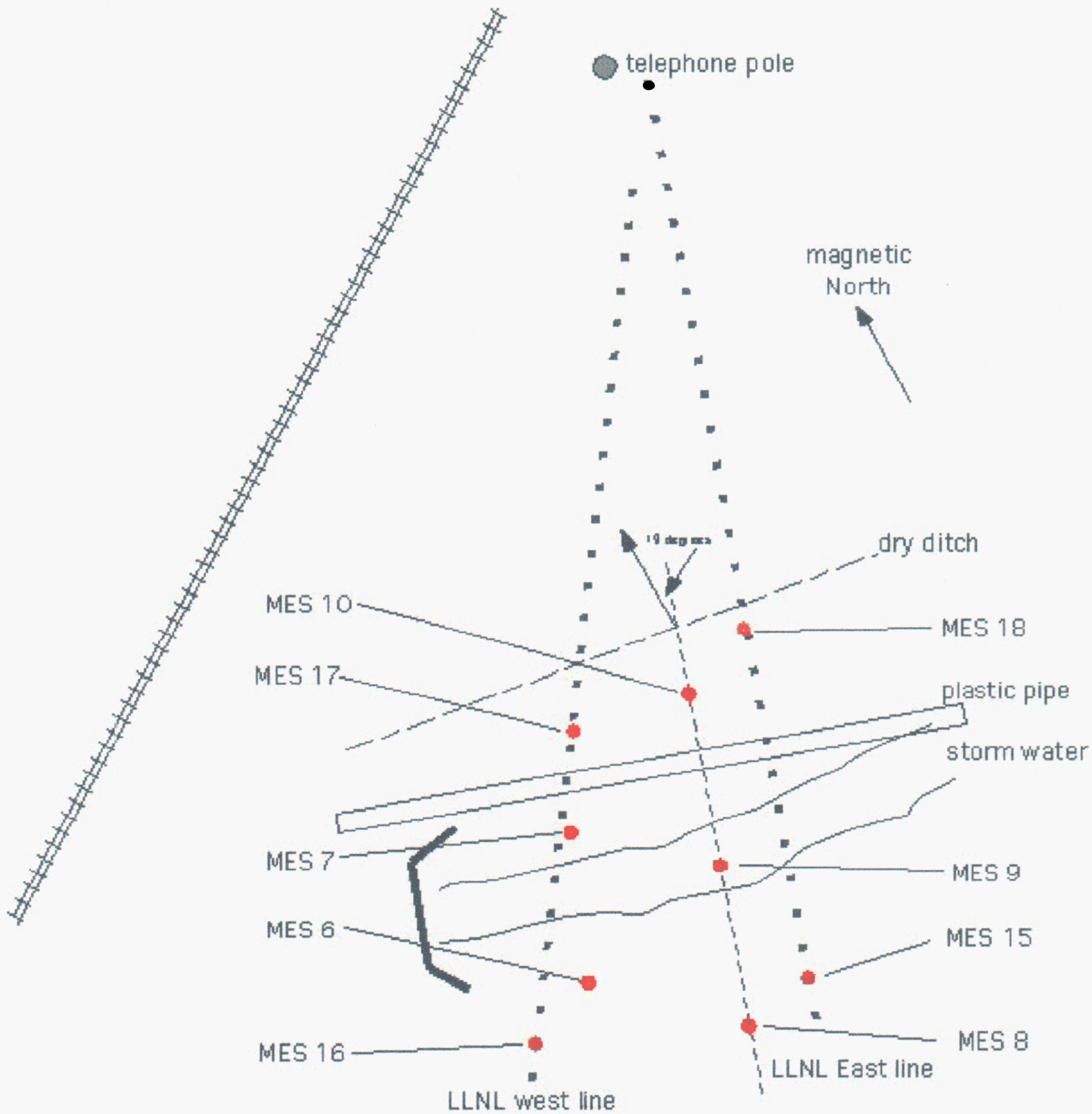


Figure 1. Low frequency spectra of magnitude and phase of an A-014 outfall sample as measured in the laboratory by Olhoeft during the last phase of this project (circa. 2001). The important feature in the PCE contaminated sample is a unique minimum and adjacent maximum. The uncontaminated sample does not show this feature. Notice that there is a difference in the magnitude spectra between clean and contaminated sample but this difference could not reliably be identified at site because of natural variability in soil resistivity.



A014 outfall site

Figure 2. Plan view of the A-014 outfall test site. The electrode arrays for the two LLNL surface surveys are shown relative to the MIT borehole locations (MES 16, MES 17, MES 15 and MES 18) and the Blackhawk borehole locations (MES 7, MES 6, MES 8 and MES 10).

A014 Outfall Site
April 2003

Figure 3. Looking east across the A-014 Outfall Site. The dashed lines are the approximate locations of the LLNL surface survey lines. Only the southern half of each survey line is shown in this view.

A014 Outfall Site
April 2003

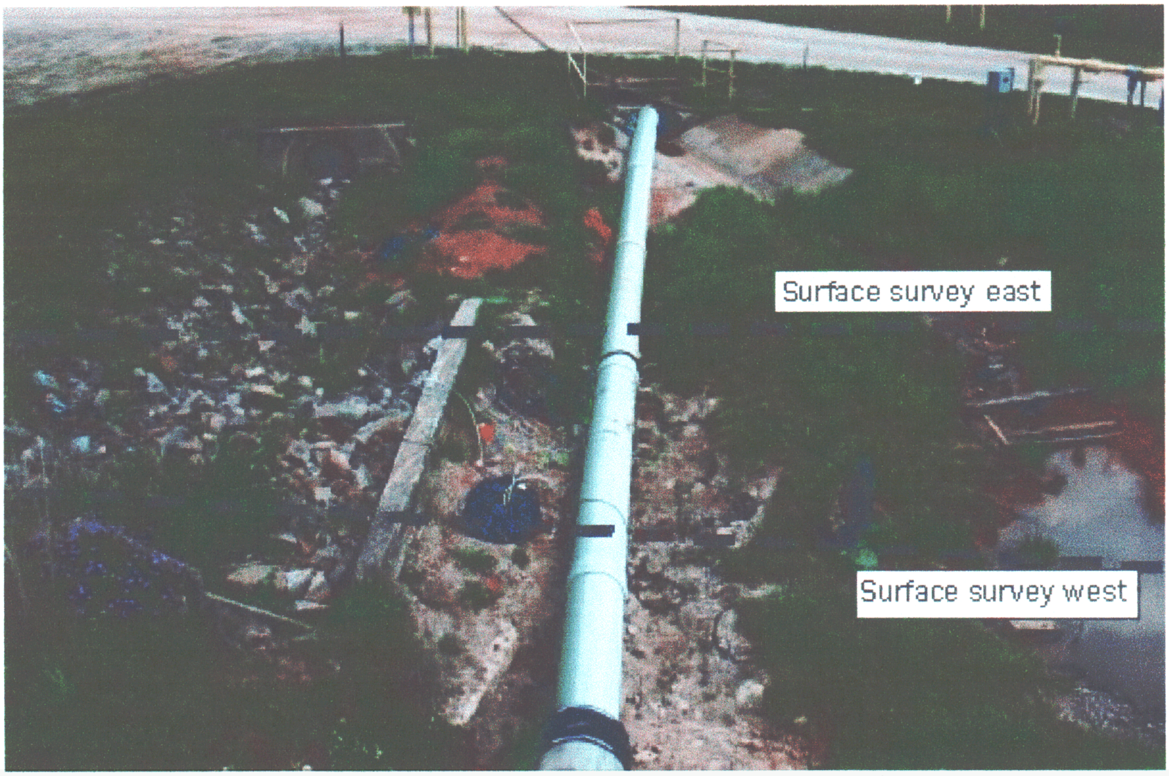


Figure 4. Looking east across the A-014 Outfall Site. The dashed lines are the approximate locations of the LLNL surface survey lines. Only the center section of each survey line is shown in this view.

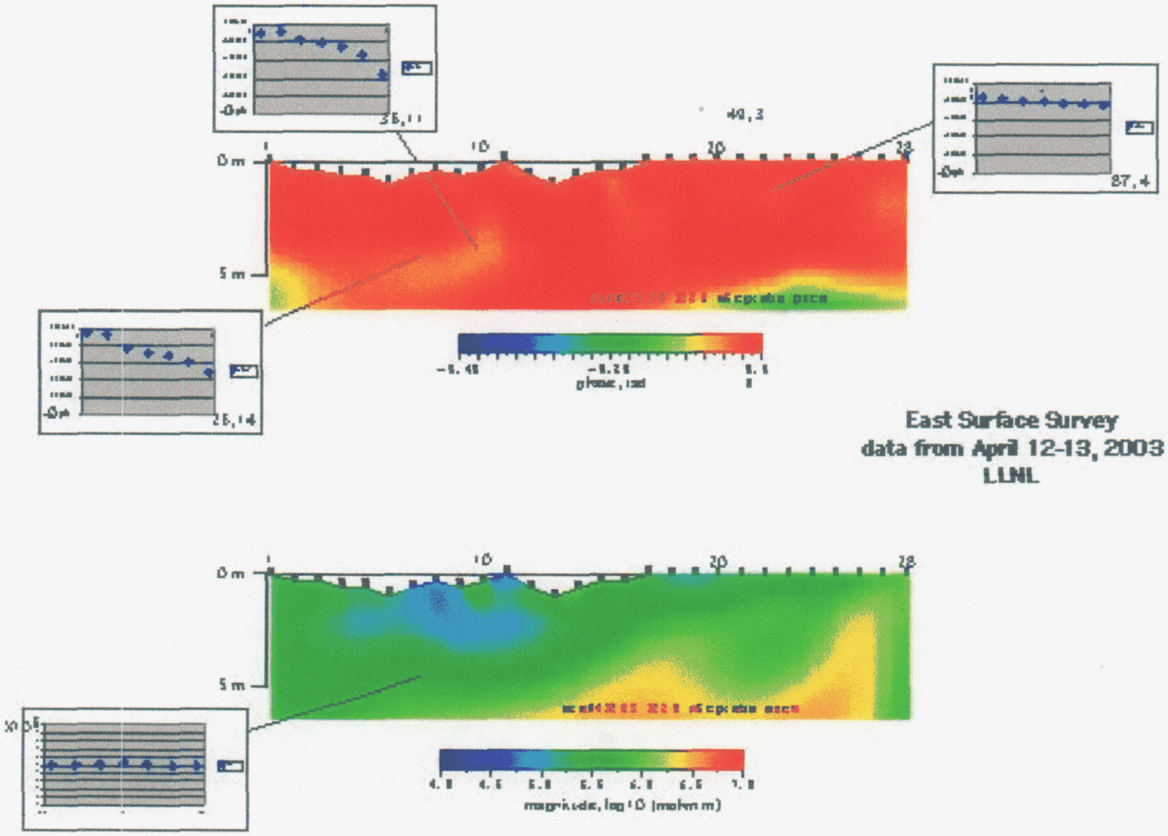


Figure 5. Phase and magnitude tomographs at 8.0 Hz for the east surface survey. The spectral content between 0.125 and 8.0 Hz for a few selected pixels is also shown.

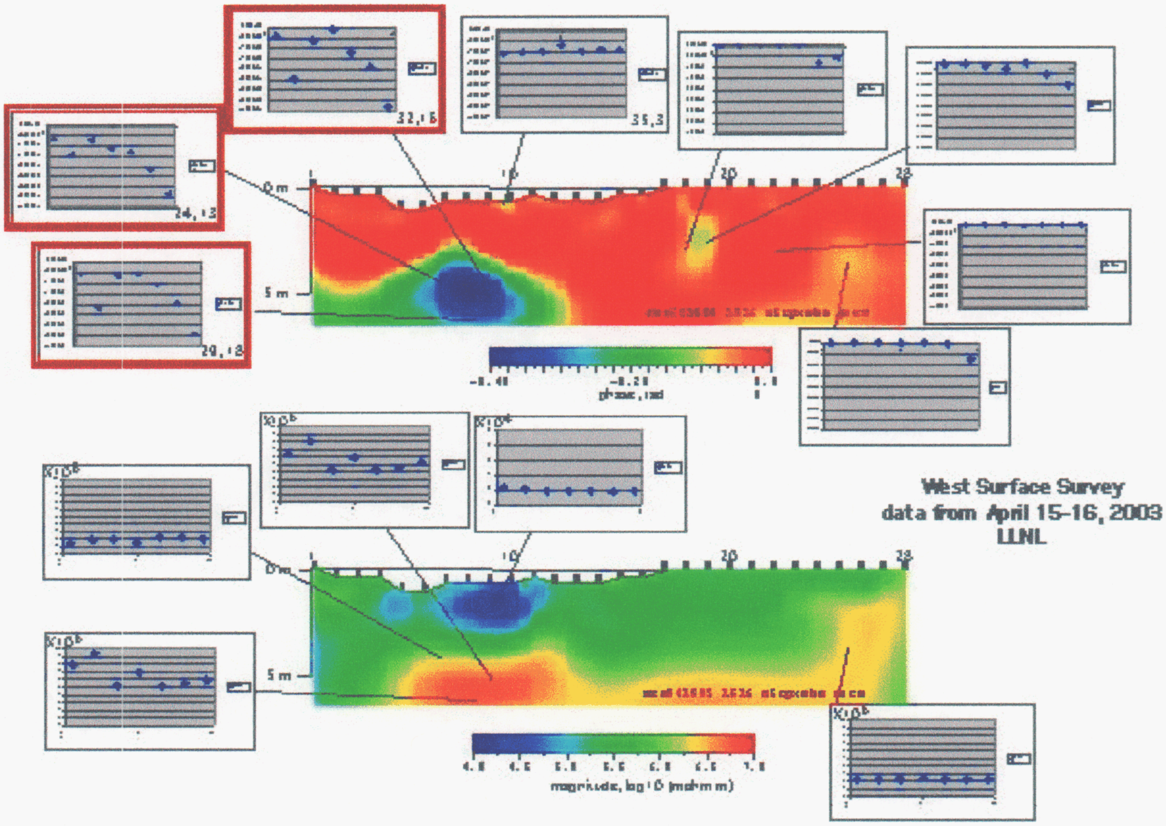


Figure 6. Phase and magnitude tomographs at 8.0 Hz for the west surface survey. The spectral content between 0.125 and 8.0 Hz for a few selected pixels is also shown.

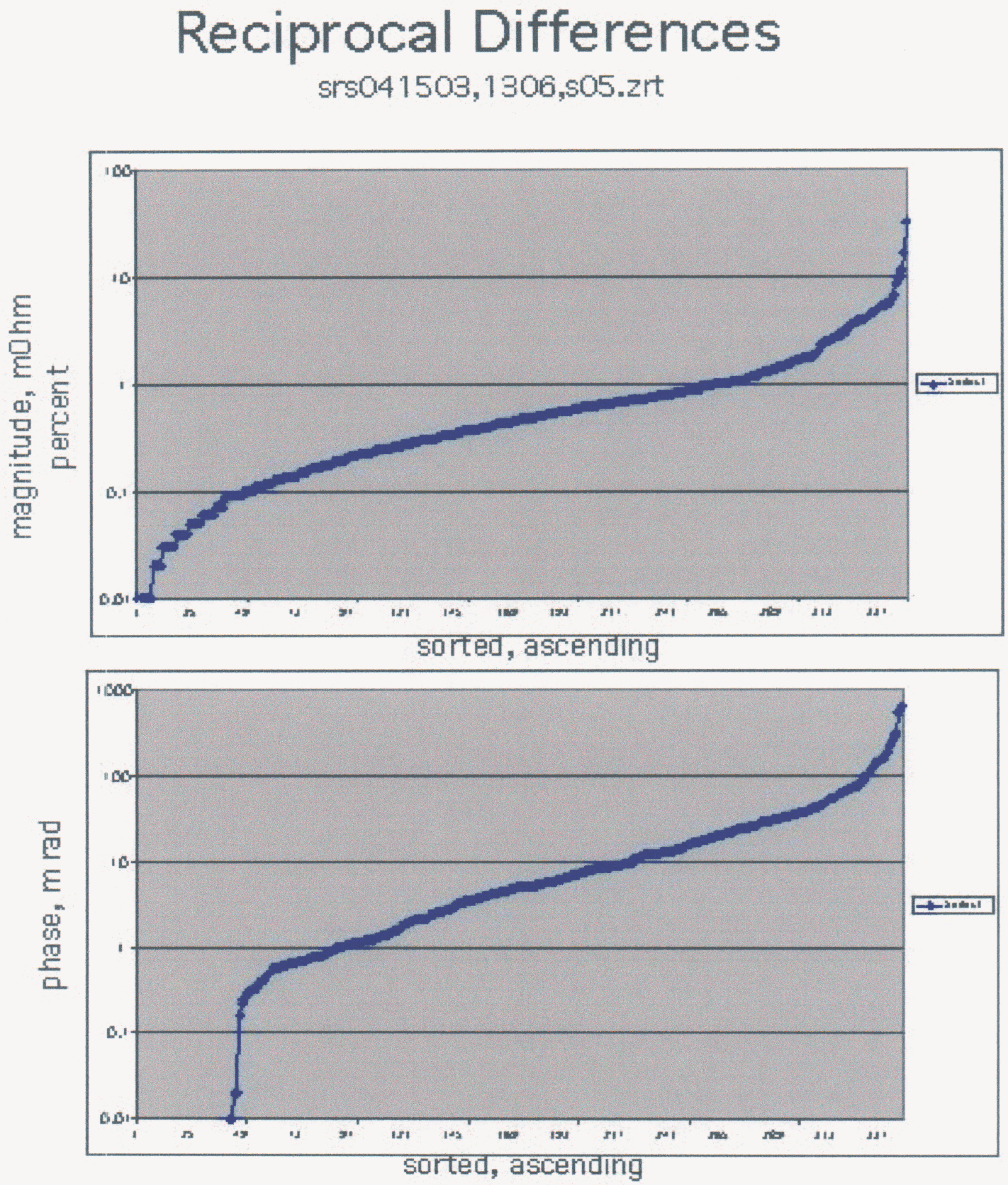
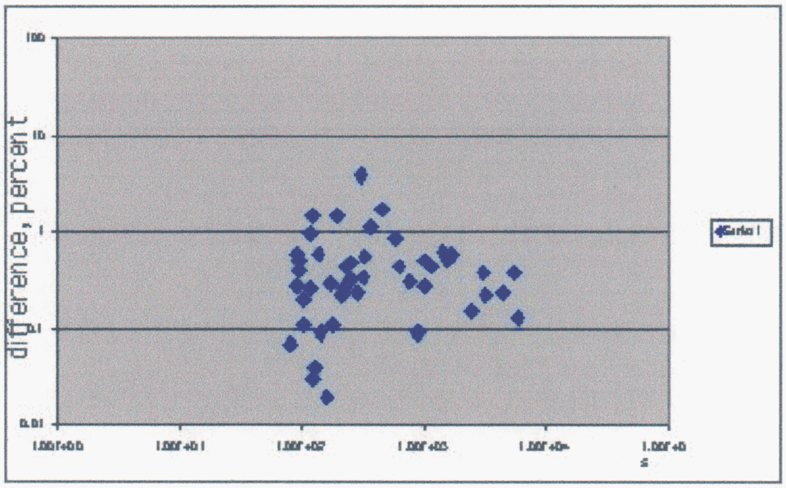


Figure 7. Impedance reciprocity. At the top the percent difference in reciprocal resistance pairs is plotted in ascending order for the 0.5 Hz data from the west survey. At the bottom the difference in reciprocal phase pairs is plotted in ascending order.

Selected Reciprocal Differences--magnitudes

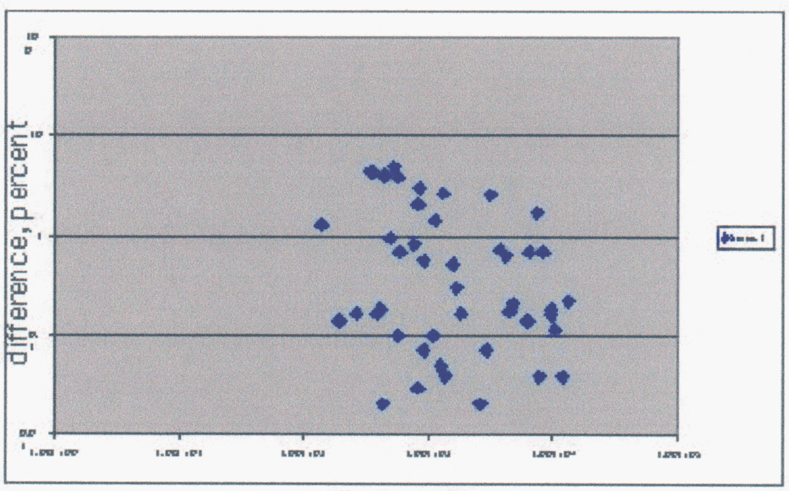
srs041503,1306,s05.zrt

data from only the southern 14 electrodes



magnitude, mOhm

data from only the northern 14 electrodes



magnitude, mOhm

Figure 8. The percent reciprocal resistance differences in figure 7 are shown for only those data taken on the southern 14 electrodes and for data from only the 14 northern electrodes of the west survey line. The percent difference is plotted as a function of the magnitude of the measured resistance.